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Monterey, California

THESIS

HYDROSTATIC PRESSURE EFFECTS ON
1/4 INCH POLYPROPYLENE LINE

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Hydrostatic Pressure Effects on
1/4 Inch Polypropylene Line

by

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ABSTRACT

The effects of hydrostatic pressure on the mechanical properties of 1/4 inch polypropylene line were investigated. The line was exposed to hydrostatic pressures of 5,000 and 10,000 psi for periods of 6, 12, and 24 hours, respectively. Upon completion of the pressurization period, the line was removed from the pressure vessel and its ultimate tensile strength recorded and compared to that of the line before pressurization. There was an increase in the tensile strength of the line as pressure increased and time progressed, with a maximum increase of 3.1 percent occurring after pressurization at 10,000 psi for 12 hours and at 5,000 psi for 24 hours. Secondly, there was no measurable difference in the relative elongation of the line after pressurization as compared to that before pressurization. The mode of failure was investigated by testing individual line fibers. Microscopic observation after failure showed no discernible difference between the mode of failure before and after pressurization. In each case, the fibers presented a somewhat jagged edge and the outer portions of the fiber appeared to have peeled back.

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STU	Submersible Test Unit
NCEL	Naval Civil Engineering Laboratory
NWC	Naval Weapons Center
MIT	Massachusetts Institute of Technology
WHOI	Woods Hole Oceanographic Institution
σ_{circ}	Circumferential Stress
σ_{acial}	Axial Stress

I. INTRODUCTION

Synthetic materials have received extensive use in the ocean environment since their introduction in about 1950 [7]. They have been used in manners ranging from the use of nylon for the lifting of heavy loads, as in the recovery of the submersible Alvin, to the plexiglass construction of the underwater observatory NEMO. The advantages of the synthetic materials over their metal counterparts are that they are lighter, giving a greater strength to weight ratio, and they are more flexible. Polypropylene, the lightest of the synthetics, is positively buoyant in sea water and has been used for anchor and buoy lines as well as providing an inverted catenary recovery line [6].

Muroaka, at NCEL, has done extensive work in the field of the biodeterioration of materials in the deep ocean. In one particular test, nylon and polypropylene lines were attached to a Submersible Test Unit (STU) which was left at a depth of 6800 feet for a period of 13 months. The tensile strength of these lines was recorded before and after submergence with the result that the tensile strength had increased by approximately 8 percent after exposure to the ocean environment [6].

Considerable effort has also been applied to solving the problem of line dynamics; that is, the determination of the dynamic response of a synthetic line with one end attached to a platform with six degrees of freedom, and the other end attached to a heavy weight suspended in the ocean. The mathematical models developed to date have not accurately predicted measured results [5].

Muraoka's work and the line dynamics problem provided the impetus for this study. It was hoped that a thorough investigation of the effects of hydrostatic pressure on the mechanical properties of synthetic materials would provide an input to the line dynamics problem such that a better mathematical model could be developed.

The first step was to obtain a pressure vessel so that the hydrostatic pressures encountered in the deep ocean environment could be simulated in the laboratory. This was accomplished by using a 16-inch Naval projectile in the construction of a pressure testing facility. A description of the Naval Postgraduate School pressure testing facility follows this introduction.

Primarily due to the availability of material, 1/4 inch polypropylene line was chosen as the test material. The effects of hydrostatic pressure on the mechanical properties of the polypropylene line were determined by exposing the line to various hydrostatic pressures for different periods of time and comparing the mean ultimate tensile strength of the line before and after exposure. An attempt was also made to determine the mode of failure by considering individual fibers of the line and examining them microscopically after failure.

II. PRESSURE VESSEL DESCRIPTION

In the past decade, considerable effort has been expended in the exploration and utilization of the deep ocean for such purposes as Naval operations, commercial enterprises and scientific research. Hydrostatic pressure, in addition to corrosion, presents one of the most serious problems in the effective utilization of the deep ocean environment; pressure increases at a rate of about 0.44 psi per foot of depth with 16,000 psi approximately representing the deepest points in the ocean.

The Naval Postgraduate School pressure testing facility utilizes an MK13, Mod 2, 16-inch high capacity Naval projectile as the pressure vessel; the basic installation was received by the Naval Postgraduate School in 1968 from NWC China Lake. It is believed that this method was first used by Maurice Ewing, Allan Vine and Joe Worzel at Lehigh University [1], and subsequently at MIT, WHOI, NCEL and NWC China Lake.

Of the various types of projectiles available, the 16-inch high capacity type was originally chosen because it offered the largest internal volume. Figure 1 shows the basic dimensions of this projectile and Figure 2 the internal dimensions of the Naval Postgraduate School pressure vessel. The exact composition of the steel used in the production of these projectiles is not known; however, the alloy is generally described as a special high-capacity projectile Chromium-Nickel-Molybdenum alloy steel with a minimum tensile yield strength of 78,000 psi, an ultimate tensile strength of 105,000 psi and an elongation of 18 percent [4].

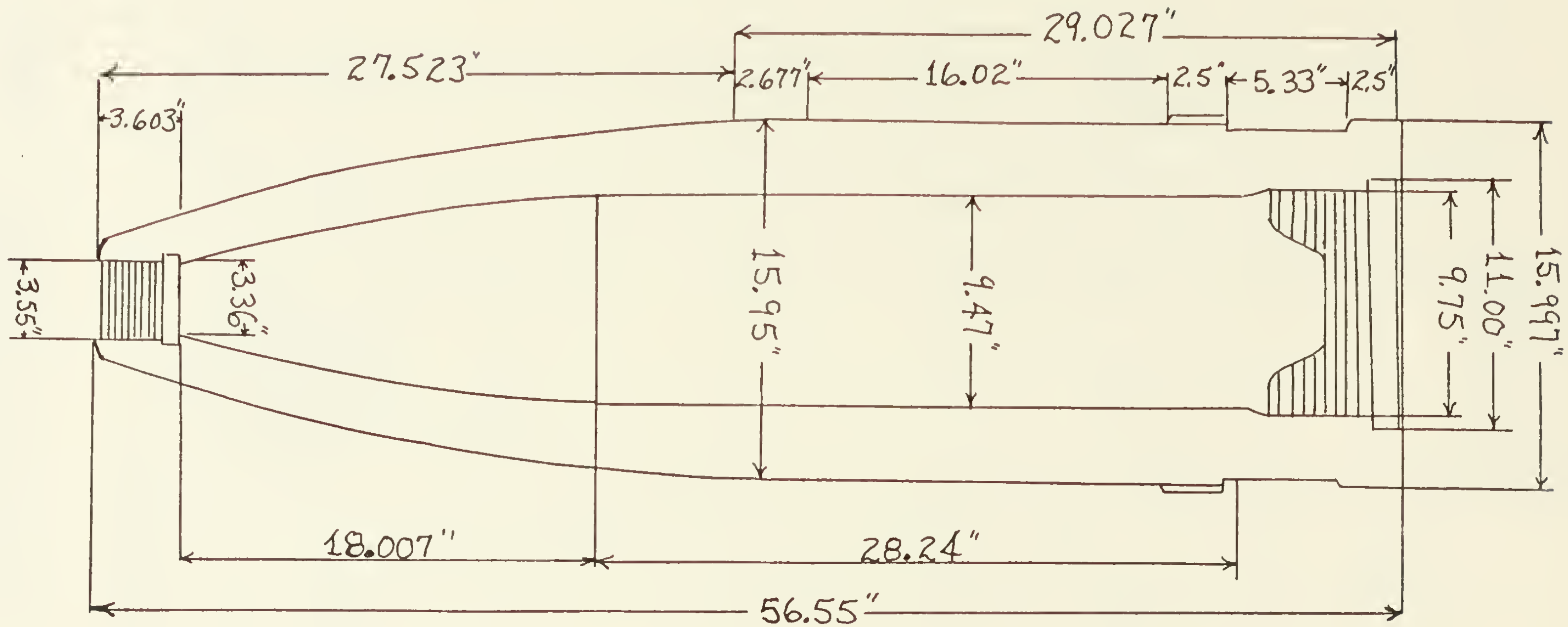

FIGURE 1. Basic Dimensions of the Mk 13, Mod 2, High Capacity, 16 Inch Naval Projectile.

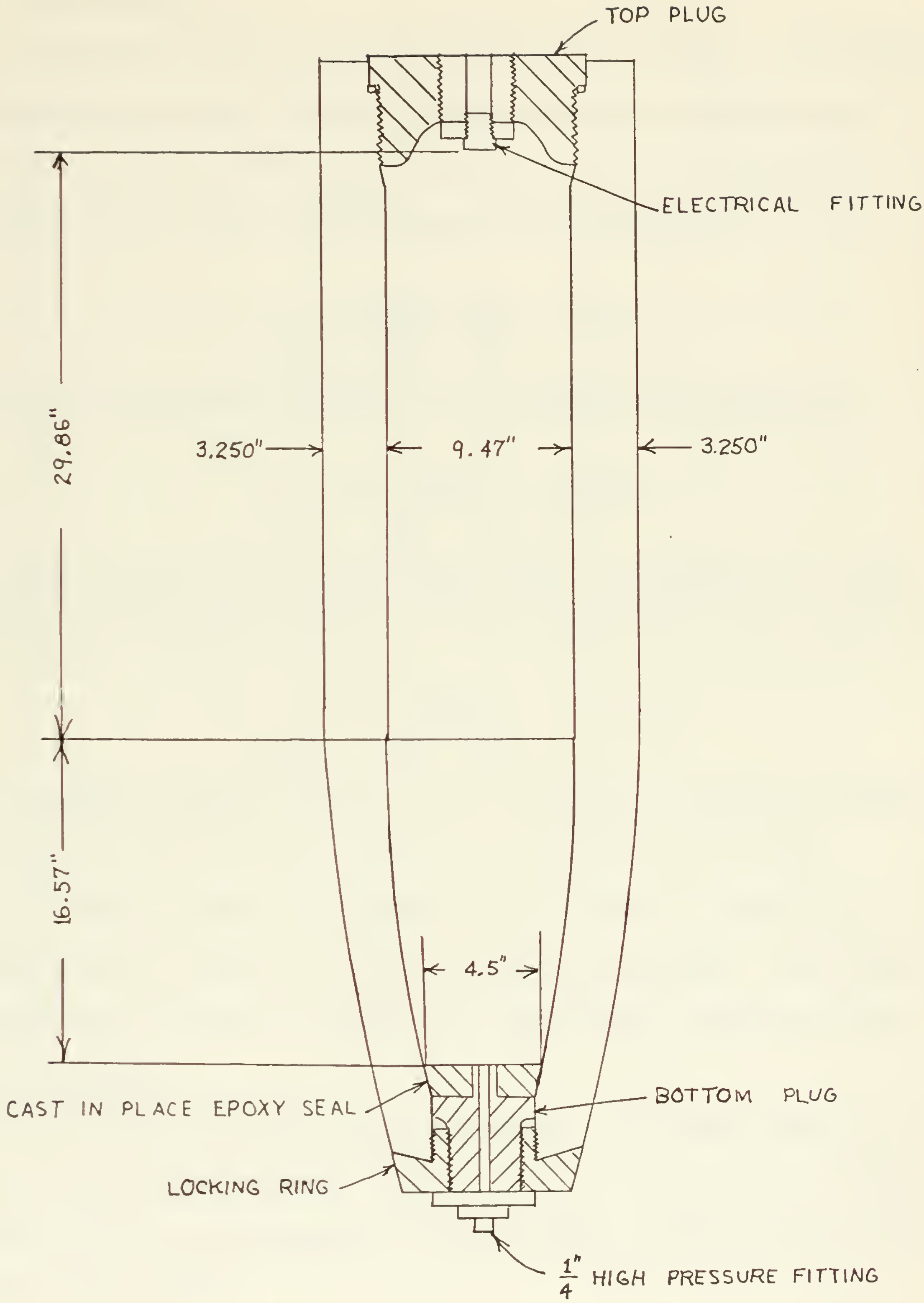

FIGURE 2. Internal Dimensions of the Naval Postgraduate School Pressure Vessel.

A. PROOF TESTING

The pressure vessel is a typical thick walled cylinder, and as shown by NCEL [4], the Lamé solution is applicable to the calculation of stresses in such a vessel. Lamé's solution for the circumferential stresses on the interior of the vessel can be expressed as

$$\sigma_{circ} = p\frac{(OD^2 + ID^2)}{(OD^2 - ID^2)} = 1.089p$$

and the circumferential stresses on the exterior of the vessel as

$$\sigma_{circ} = 2p\frac{(ID^2)}{(OD^2 - ID^2)} = 2.089p$$

The axial stresses in the thick walled vessel are assumed to be uniform across the thickness of the wall, and their magnitude can be calculated by

$$\sigma_{axial} = p\frac{(ID^2)}{(OD^2 - ID^2)} = 0.545p$$

A series of proof tests were run on the 16-inch projectile at NCEL [4] and the following conclusions and recommendations were made:

1. Pressure vessels fabricated from Mk 13, Mod 2, 16-inch Naval projectiles are useful up to 20,000 psi internal pressure. With proper precautions to prevent corrosion of the vessel body, they may be used with sea water.

2. It was recommended that the converted 16-inch Naval gun shells not be subjected to pressure cycling service at 20,000 psi until experimental data has been generated on which reliable and safe cycling pressure limits can be based.

B. COMPONENT DESCRIPTION

A schematic diagram of the pressure testing facility as installed at the Naval Postgraduate School is shown in Figure 3. Front and side view photographs of the installation are illustrated in Figures 4 and 5 respectively. A discussion of the various components of the system follows.

1. Hydraulic Power Source

The Sprague Model S-440 Power Unit, shown in Figure 6, provides a compact, high pressure, low volume hydraulic power source which is used to obtain internal pressures in the pressure vessel ranging from 0 to 20,000 psi. The S-440 Power Unit operates from a compressed air supply and consists of a Sprague Model S-216C-100 Air-Operated Pump, muffler, Lubro-Control Unit, driving air shutoff valve, output pressure gage, pressure outlet, bleed valve and baseplate.

The S-216C-100 pump is a piston-type, air-operated, boost pump incorporating an automatically operated, snap action, air selector valve. This pump develops high pressures through application of the principle of differential areas. The pump employs a large area piston, air-driven at low pressure, to drive a small piston that displaces a small volume of fluid at high pressure. The output pressure developed by the small area piston is determined by the ratio between the area of the driving piston, the area of the driven piston and the operating air pressure applied. The 20,000 psi pump used in the Naval Postgraduate School installation has a 1:200 pumping ratio; i.e., an input air pressure of 100 psi will enable the pump to produce a fluid pressure of 20,000 psi. This same ratio applies to all but the lowest pressure ranges, where the efficiency of the pump decreases due to the increasing effect of friction in the

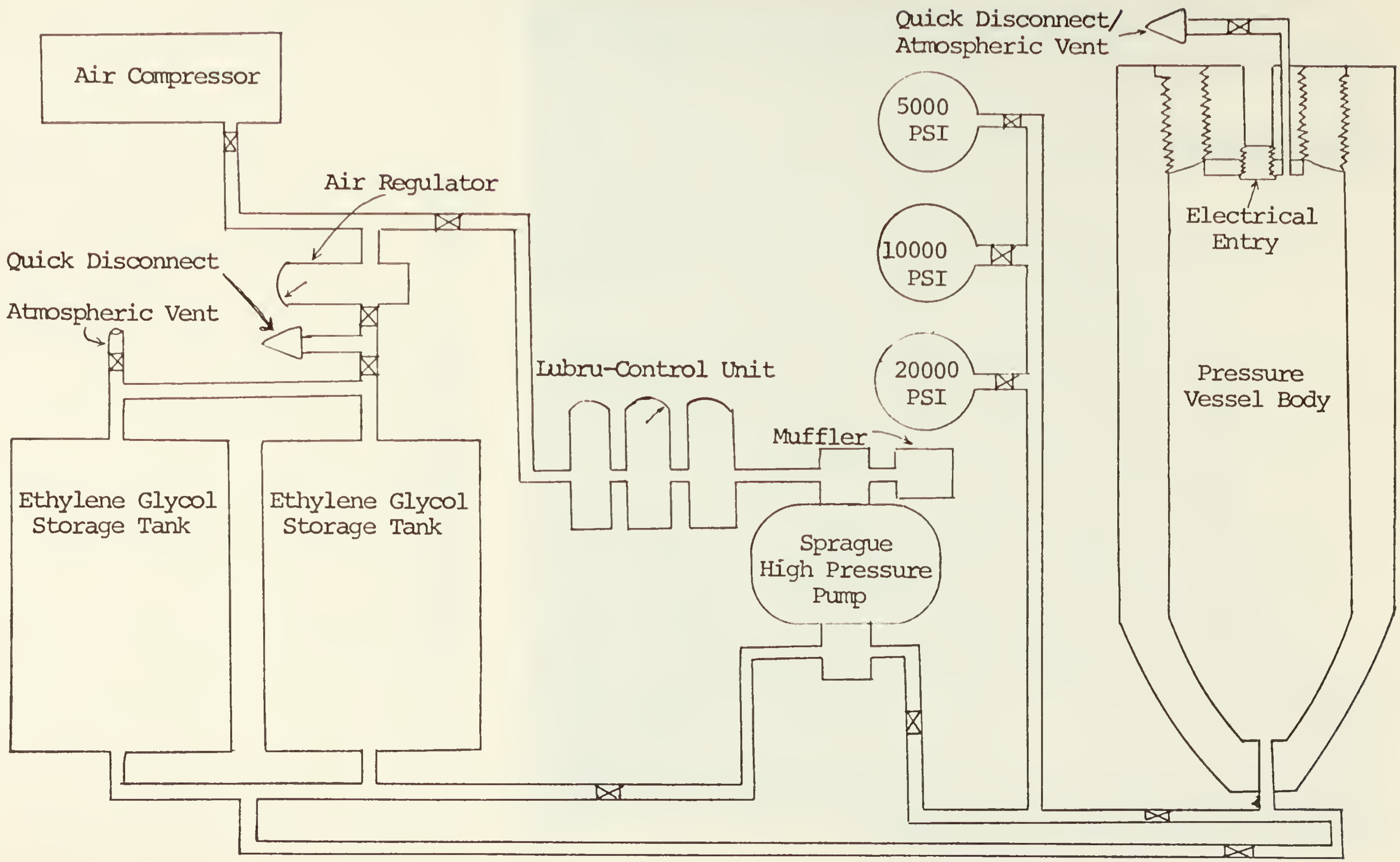

FIGURE 3. Schematic Diagram of the Naval Postgraduate School Pressure Facility

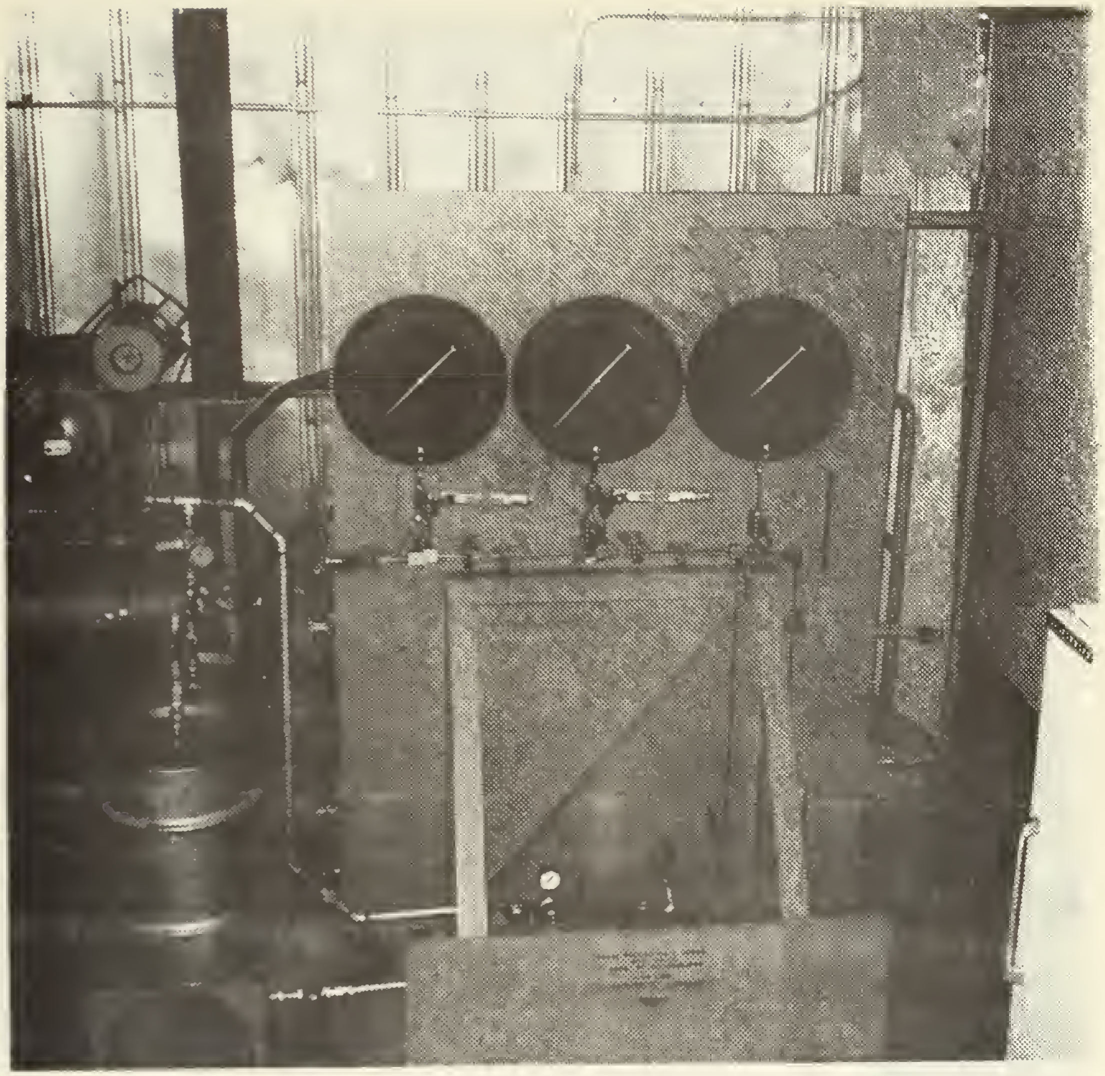

FIGURE 4. Naval Postgraduate School
Pressure Testing Facility.

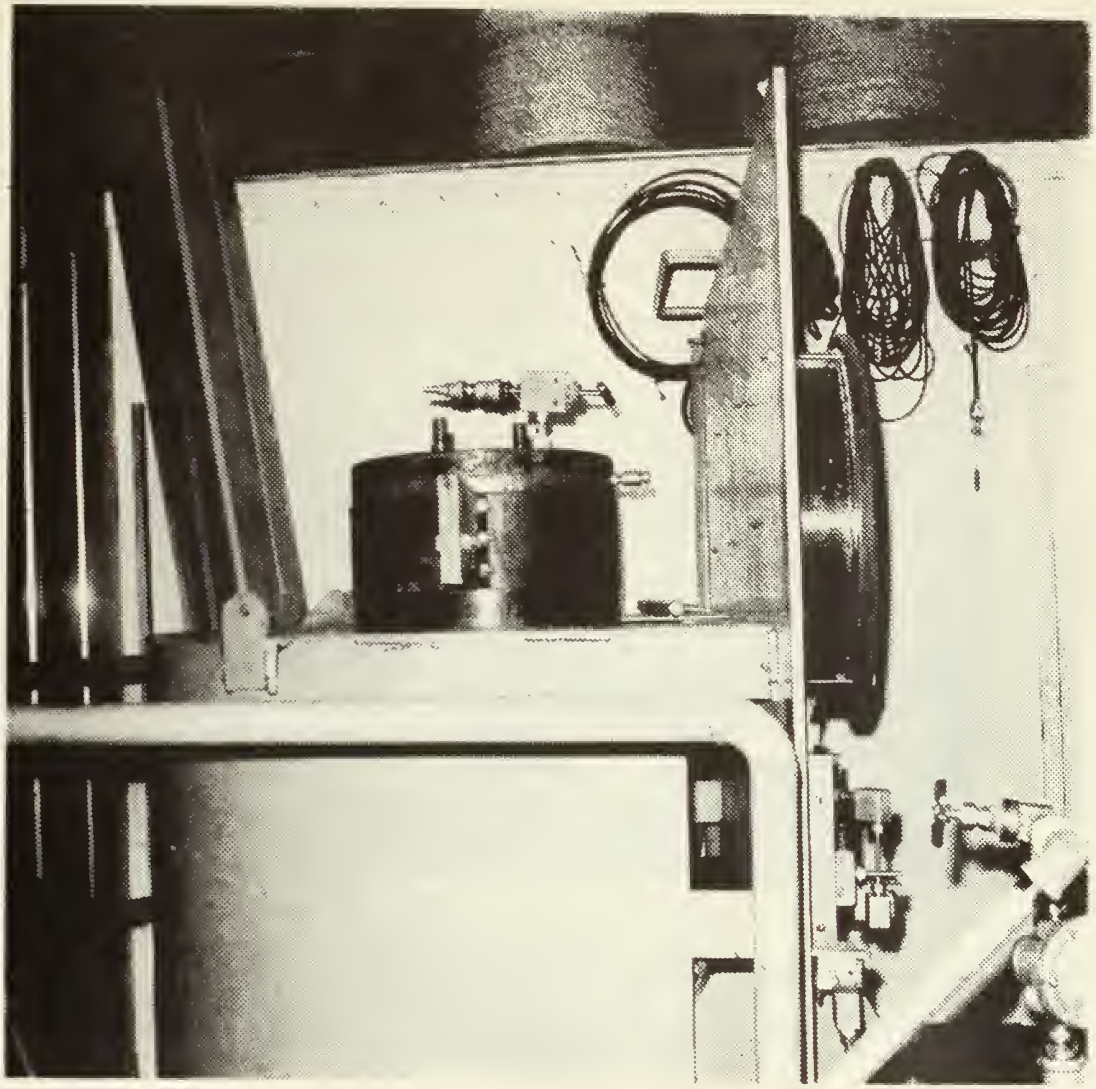

FIGURE 5. Side View of the Naval Postgraduate School Pressure Testing Facility Showing Position of Pressure Vessel.

FIGURE 6. Sprague Model S-440 Hydraulic Power Unit.

pump at low air pressures. The advantage of this type of pump is that when the input air pressure is regulated to a certain pressure, it is possible to leave the pump unattended while the prescribed output pressure is being built up in the pressure vessel. When the pressure in the vessel reaches the preset output pressure (200 times the input air pressure) the pump stalls and automatically shuts down. It will only resume pumping (again automatically) if the pressure on the output side drops, or the input air pressure increases.

The Lubro-Control Unit, located in the driving air supply line, provides filtration, regulation and lubrication of the air supply.

The air shutoff valve is positioned in the driving air supply line between the Lubro-Control Unit and the high pressure pump and is used to control the operation of the pump.

2. Air Compressor

An Ingersoll-Rand Type 30, Model 71T air compressor provides low pressure air at 100 psi to the Strague Hydraulic Power Unit described above; it is a 10 horsepower, two-stage, single acting, air-cooled compressor. It is equipped with a water-cooled aftercooler which reduces the discharge temperature of the compressed air and facilitates removal of water vapor and oil vapor, and is also equipped with dual speed regulation which permits a manual selection between constant speed control (compressor is unloaded at a predetermined pressure while the motor continues to operate) and automatic start and stop control (makes or breaks electrical contact to the motor at predetermined pressures).

3. Fluid Medium

The fluid medium used in the Naval Postgraduate School installation is ethylene glycol, a non-corrosive fluid. The sea water environment (Salinity 33.4 parts per thousand) was obtained by filling a cylindrical

tube, approximately 2 feet in length, 6.5 inches in diameter and closed on one end, with sea water and sealing the open end with a flexible diaphragm and hose clamp; the flexible diaphragm served to transmit the hydrostatic pressure of the pressure vessel to the sea water environment.

4. Fittings, Valves and Tubing

The high pressure fittings and valves are rated for 60,000 psi use and the high pressure tubing for 30,000 psi use; all are fabricated from type 316 stainless steel. The tubing is 1/4 inch O.D. by .083 inch I.D. and connections are of the union type. The male tube has a 59 degree conical seating surface that fits into a corresponding 60 degree female conical seat in the body. The male tube and inner sleeve have left hand threads; the gland nut and opening in the body have right hand threads. When the gland nut is slipped over the sleeve and screwed into the opening in the body, the sleeve is tightened on the tubing at the same time that the conical seating surfaces are being sealed. Figure 7 shows the make-up of a typical connection between high pressure tubing and a female fitting.

Piping on the low pressure side of the pump and all air piping is 3/4 inch galvanized pipe; standard 3/4 inch gate valves are used throughout the low pressure piping.

5. Electrical Entry

Electrical entry is gained to the interior of the pressure vessel via a 7 conductor plug; location of the electrical plug is illustrated in Figures 2 and 3.

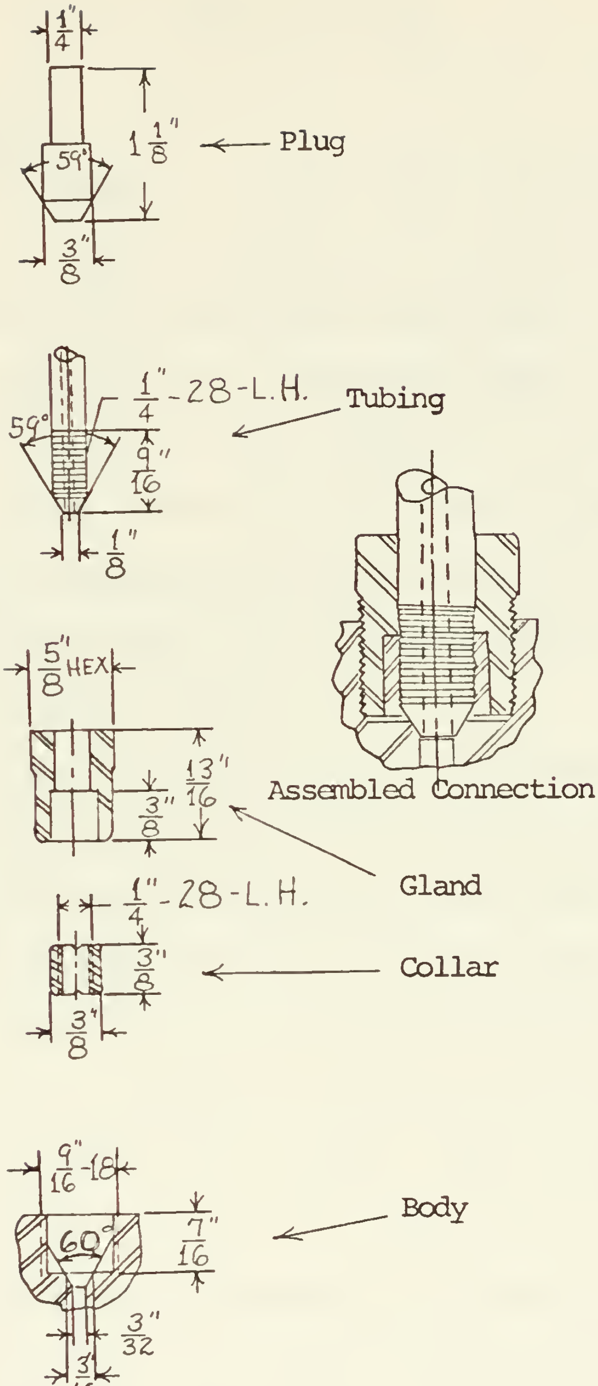

FIGURE 7. Typical Connection Between High Pressure Tubing and Female Fittings.

III. TESTING PROCEDURE

A. DATA COLLECTION

The purpose of the experiments was to compare the mechanical properties, namely tensile strength and elongation, of 1/4 inch polypropylene line before pressurization to those after pressurization at various pressures and for varying durations. Because no method had been developed for tensile testing inside the pressure vessel, i.e., in situ, and due to limitations on the time available to devise such a method, testing of the line samples was commenced within approximately 15 minutes after removal from the pressure vessel. All testing was done on the Instron testing machine illustrated in Figure 8.

The tensile testing device used for holding the polypropylene line is also illustrated in Figure 8 (arrow). The line was reeved around the inside of the device so that the line would not slip when tension was applied. The tensile testing device was designed in such a way that the line was tangent at top and bottom to pieces of round stock so that when tension was applied failure occurred between the two points of tangency, not at the points of contact with the device. This method of testing the line proved satisfactory with the exception that it was not possible to precisely measure the absolute elongation of each sample since some elongation did occur inside of the device; a typical elongation of approximately 60 percent was recorded. There was no measurable difference in the relative elongation of the line after pressurization compared to that before pressurization.

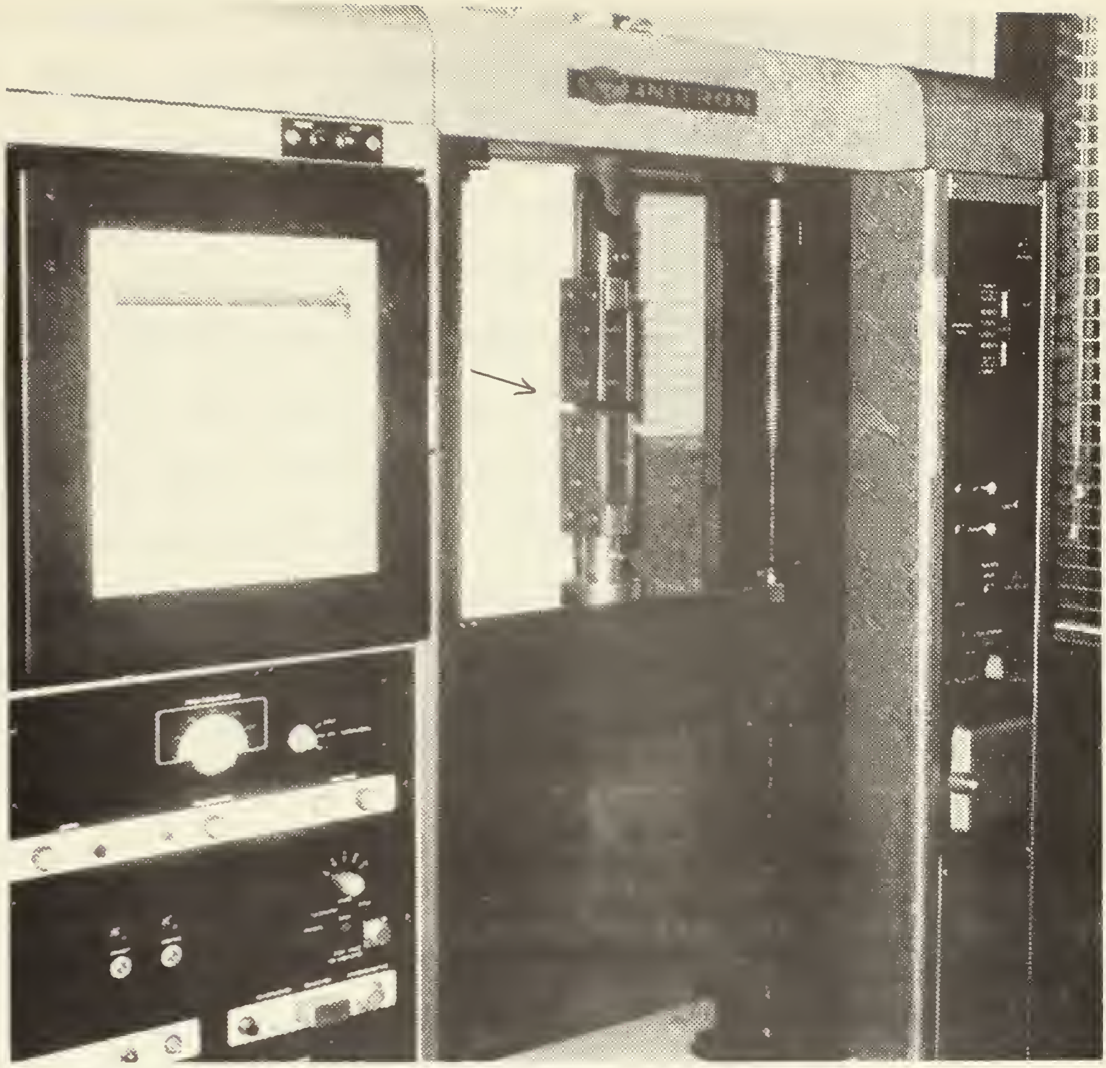

FIGURE 8. Instron Tensile Testing Machine.

B. DISCUSSION OF DATA

Table 1 presents a summary of the data collected. A plot of mean ultimate tensile strength versus time (pressure held constant) is shown in Figure 9, and Figure 10 shows a plot of mean ultimate tensile strength versus pressure (time held constant). In all cases the tensile strength of the line increased after pressurization. However, the fact that the increase in the tensile strength of the line after pressurization at 10,000 psi for 12 hours was not further increased after pressurization at 10,000 psi for 24 hours was unexpected.

A confidence interval for the true mean of the population having the degree of confidence (1 - α) was calculated for each set of data. It is assumed that the sample population has a normal distribution. The statistic,

$$t = \frac{\bar{x} - \mu}{s/\sqrt{\mu}}$$

is the value of a random variable having the Student t-distribution with n-1 degrees of freedom, where μ is the mean of the normal population from which the sample is taken, thus,

$$\left\{ \bar{x} - t_{\frac{\alpha}{2}} \cdot \frac{s}{\sqrt{n}} < \mu < \bar{x} + t_{\frac{\alpha}{2}} \cdot \frac{s}{\sqrt{n}} \right\} = 1 - \alpha$$

where, $\bar{x}$ = population mean

t = t-statistic

s = standard deviation of the population

n = number of samples in the population

1 - α = confidence interval

μ = true population mean

TABLE 1. SUMMARY OF RESULTS

Pressure/Duration	Mean Ultimate Tensile Strength (Lbs) (10 Runs)	Standard Deviation $(Lbs)^2$	Confidence Interval For True Mean, μ (Lbs)
"0" PSI: Datum	740.6	11.1	$734.2<\mu<747.0$
10,000 PSI/6 Hours	755.4	13.8	$747.4<\mu<763.4$
10,000 PSI/12 Hours	771.6	15.3	$762.7<\mu<780.5$
10,000 PSI/24 Hours	758.3	8.6	$753.3<\mu<763.3$
5,000 PSI/6 Hours	750.6	17.7	$740.3<\mu<760.9$
5,000 PSI/12 Hours	746.5	14.9	$737.9<\mu<755.1$
5,000 PSI/24 Hours	770.7	20.1	$759.0<\mu<782.4$

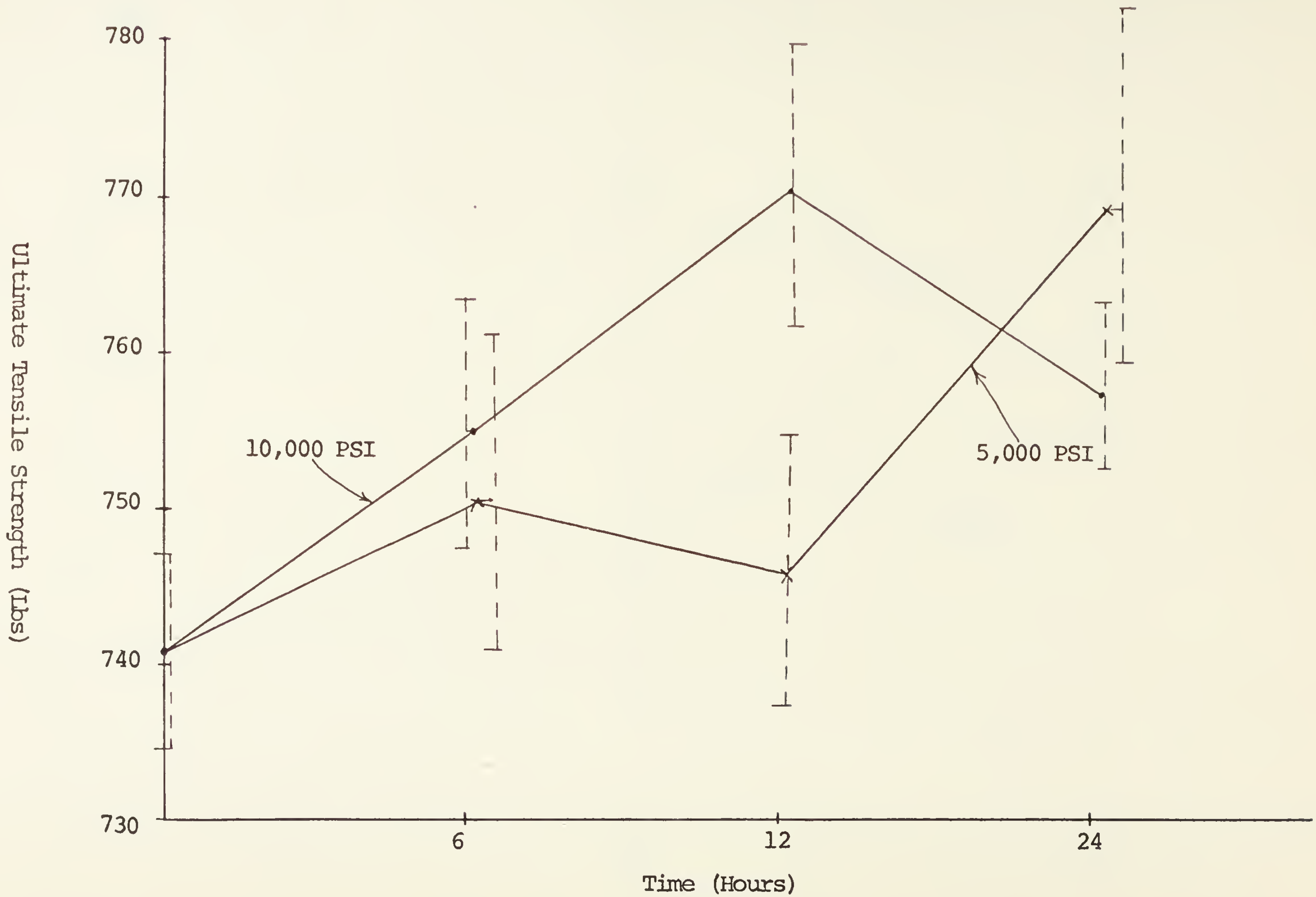

FIGURE 9. Plot of Ultimate Tensile vs Time

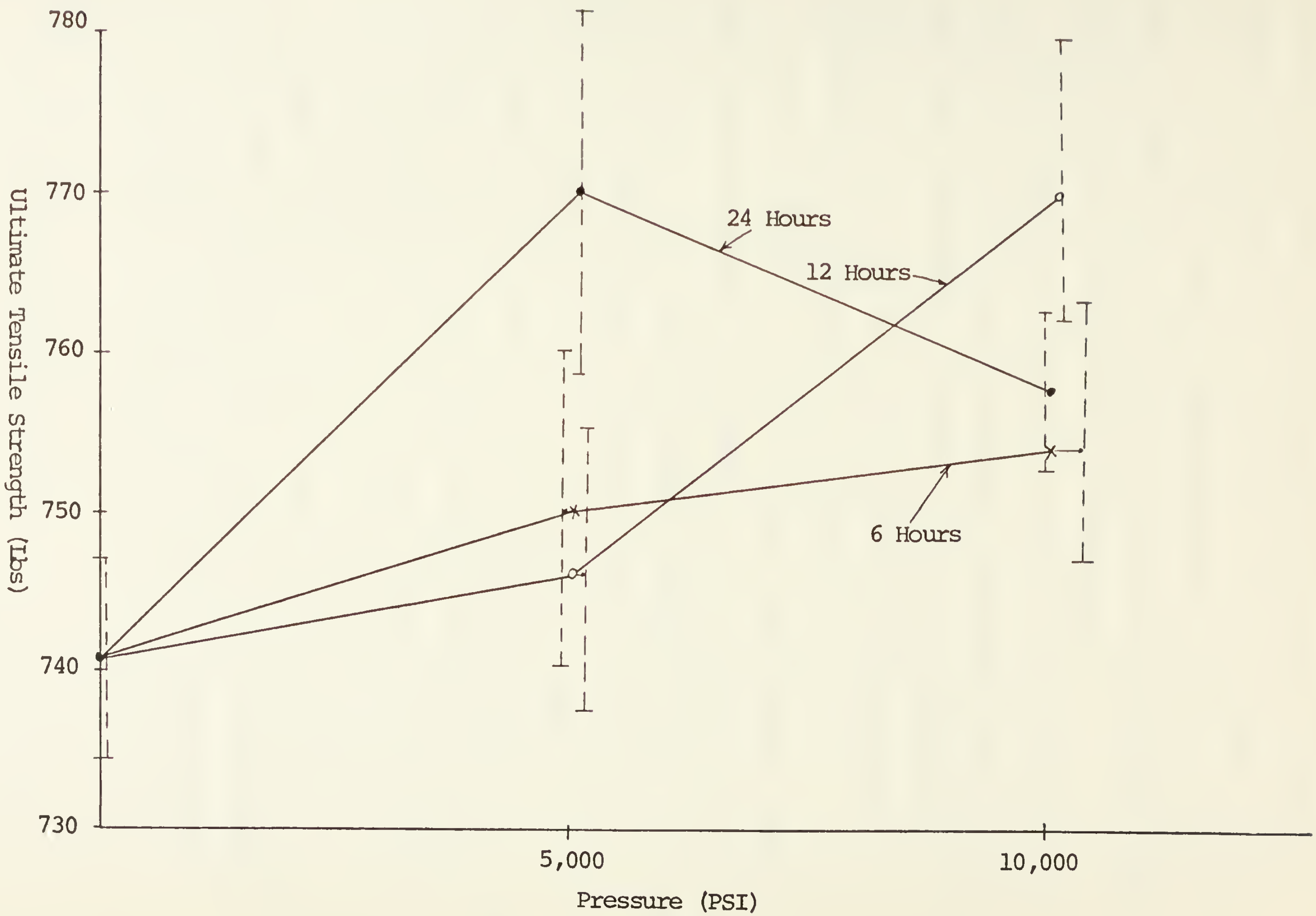

FIGURE 10. Plot of Ultimate Tensile Strength vs Pressure

This inequality provides an exact 1 - α confidence interval for μ provided the assumption of normal population is true. A confidence interval of 90 percent (α = .10) was calculated for the data collected and is tabulated in Table 1. These confidence intervals are also indicated as dotted lines on the plots of ultimate tensile strength versus time and pressure in Figures 9 and 10 respectively.

Inconsistencies in the data could exist due to the fact that the temperature of the sea water environment to which the line samples were exposed was uncontrollable. Synthetic materials are sensitive to temperature variations [2], and the temperature of the sea water environment did vary during some of the tests.

In initial attempts to collect the data presented above, inconsistencies were encountered as progression was made through a coil of line. It was generally found that the mechanical properties of the line changed as the coil of line was used. Insufficient data was collected to state this as a fact; however, it is felt that due to the compaction of the outer layers of line on the coil, the line nearer the center of the coil is stronger. The line samples that were used to collect the data presented above were removed from the outer portions of a large diameter coil of line in order to avoid the possibility just described.

A statistical Student t-test for comparing two sample means [3] was run on the data collected in order to make an unbiased decision about the relative values of the mean ultimate tensile strength before and after pressurization. The statistical test was based on the null hypothesis:

H_o: $\bar{x}_p - \bar{x}_u$ = 1 percent of $\bar{x}_u$ = 7.406

where, $\bar{x}_p$ = mean ultimate tensile strength after pressurization

$\bar{x}_u$ = mean ultimate tensile strength before pressurization

The alternate hypothesis is stated as:

H_I: $\bar{x}_p - \bar{x}_u > 7.406$

If the null hypothesis can be rejected, then the alternate hypothesis can be unbiasedly accepted at some level of significance. It is necessary to assume that the sample populations have a normal distribution in using the Student t-distribution; this appears to be a reasonable assumption for the data collected. The t-statistic was calculated using the formula:

$$t = \frac{(\bar{x}_p - \bar{x}_u) - \delta}{\sqrt{(n_p - 1)S_p^2 + (n_u - 1)S_u^2}} = \sqrt{\frac{n_p n_u (n_p + n_u - 2)}{n_p + n_u}}$$

where, $\bar{x}_p$ and $\bar{x}_u$ are as indicated above

$n_p = n_u$ = number of samples in each population = 10

δ = 1 percent of $\bar{x}_u$ = 7.406

s = population variance

The result of comparing the mean ultimate tensile strength of the line after pressurization to that before pressurization via the Student-t test described above was that the null hypothesis could be rejected and the alternate hypothesis accepted at a 97.5 percent level of significance for the cases where the line samples were exposed to hydrostatic pressures of 10,000 psi for 12 and 24 hours and 5,000 psi for 24 hours; this implies that in these cases the tensile strength of the line increased by <u>at least</u> 1 percent of $\bar{x}_u$ after exposure. A level of significance less than 90 percent was calculated for pressurization at 5,000 psi for 6 and 12 hours and 10,000 psi for 6 hours. Hence, the effect of hydrostatic pressure on the breaking strength of 1/4 inch polypropylene line is dependent on the duration and degree of pressurization.

C. MODE OF FAILURE

An attempt was also made to determine the mode of failure of the polypropylene line. This was accomplished by testing individual fibers of the line and observing them under a microscope after failure. Figure 11 shows the microscopic photographs of individual line fibers that were broken before pressurization and after pressurization at 10,000 psi for 6 hours. In the upper portion of each photograph, a sample of fiber before testing is shown to demonstrate the degree of necking down at failure; the blunted end of the samples is due to cutting the fiber. There is no discernible difference between the mode of failure before pressurization compared to that after pressurization. In each case there appears to be a somewhat jagged edge, and in each case the outer portions of the fiber seem to have peeled back, as in the removal of a banana peel. This is observable only in the lower right-hand photograph, but did occur in every case. In the photographs in which this is not visible, the outer fibers had peeled back beyond the field of view of the microscope.

Before Pressurization

After Pressurization:
10,000 PSI for 6 Hours

FIGURE 11. Microscopic Photographs (40X) of Individual Line Fibers After Failure.

IV. CONCLUSIONS

a. There was an increase in the tensile strength of the line for all cases as pressure increased and time progressed with a maximum increase of 3.1 percent occurring after pressurization at 10,000 psi for 12 hours or at 5,000 psi for 24 hours.

b. There was no measurable difference in the relative elongation of the line after pressurization compared to that before pressurization.

c. There is no discernible difference between the mode of failure before and after pressurization.

d. The hydrostatic pressures encountered in the deep ocean environment have no deleterious effects on the mechanical properties of 1/4 inch polypropylene line which has been exposed for 24 hours or less.

V. <u>RECOMMENDED FUTURE RESEARCH</u>

It is not possible, with the limited amount of data collected, to make any contribution which would directly solve the line dynamics problem as was originally hoped. The following areas are recommended for future research.

a. Devise a method whereby tensile testing could be accomplished *in situ*, i.e., inside the pressure vessel.

b. Conduct an *in situ* analysis of the creep characteristics of synthetic materials.

c. Develop a method of absolute temperature control for the Naval Postgraduate School pressure vessel so that more meaningful data could be collected and so that the deep ocean environment could be better simulated. A means of doing this has been described by NCEL [4].

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13. ABSTRACT

The effects of hydrostatic pressure on the mechanical properties of 1/4 inch polypropylene line were investigated. The line was exposed to hydrostatic pressures of 5,000 and 10,000 psi for periods of 6, 12, and 24 hours, respectively. Upon completion of the pressurization period, the line was removed from the pressure vessel and its ultimate tensile strength recorded and compared to that of the line before pressurization. There was an increase in the tensile strength of the line as pressure increased and time progressed, with a maximum increase of 3.1 percent occurring after pressurization at 10,000 psi for 12 hours and at 5,000 psi for 24 hours. Secondly, there was no measurable difference in the relative elongation of the line after pressurization as compared to that before pressurization. The mode of failure was investigated by testing individual line fibers. Microscopic observation after failure showed no discernible difference between the mode of failure before and after pressurization. In each case, the fibers presented a somewhat jagged edge and the outer portions of the fiber appeared to have peeled back.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Polypropylene						
Line						
Hydrostatic						
Pressure						
Strength						
Elongation						
Failure						

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